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PATENT SPECIFICATION

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COMPLETE SPECIFICATION

Temperature Control

5 We, TEXAS INSTRUMENTS INCORPORATED, of 6000 Lemmon Avenue, Dallas, Texas, United States of America, a corporation organized and existing under the laws of the State of Delaware, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

10 This invention relates to temperature control systems and more particularly to a servo-system to precisely control the temperature of an electric furnace.

15 An early stage in the manufacture of semiconductor devices, such as transistors and crystal diodes, is the preparation of a monocrystalline ingot of semiconductor material. From this ingot or crystal are cut the small bars or wafers used to form the transistor and diode elements. The electrical characteristics of semiconductor devices are determined almost entirely by the impurity content, impurity distribution and crystal structure of the semiconductor material used in their manufacture. Most of the electrical characteristics of the finished devices are therefore fixed at the stage of manufacture in which the ingot is formed, and, for best electrical characteristics, the ingot must be a single crystal structure which is entirely free of impurities and lattice defects except at the exact points where they are desired.

35 One of the most widely used processes for obtaining such a semiconductor crystal involves melting a quantity of extremely pure semiconductor material in an inert atmosphere or in a vacuum. A small piece of a crystal of the desired lattice structure, called a seed, is then placed in contact with the melt. Through careful control of the temperature of the melt and the speed of withdrawal of the seed, a crystal of crystallographic orientation identical to that of the seed may be developed between the seed and the surface of the melt. By precision control of slight changes in temperature and

withdrawal rate, a crystal of the desired size and shape can be obtained.

Because of the degree of purity which must be maintained in the semiconductor material throughout the growing process, the most practical heating method has been found to be a radio-frequency induction furnace in which the induction coils surround the lower portion of a sealed, transparent container of high temperature material such as glass or quartz. The charge of semiconductor material to be melted is placed in a graphite crucible within the container in such a position that it is surrounded by the induction coils. Such an arrangement has the advantage of allowing for continuous inspection of the semiconductor crystal during the growing process, concentration of the heating energy in the crucible and charge, and introduction of an inert atmosphere into the container to avoid contamination of the semiconductor material by gas or particles in the air which might react with the charge, as well as preventing the charge from becoming contaminated by heater electrodes or other materials which would necessarily come in contact with the charge in other types of furnaces.

By far the greatest problem in the crystal growing process described above is the precise control of the temperature. The melting point of semiconductor materials is relatively high; germanium melts at approximately 958.5° C. and silicon at approximately 1420° C. At certain times during the growing process it is desirable to bring the temperature of the molten charge very near the melting-solidifying temperature. For this reason, it has been found necessary to control the temperature to within 0.2° C. at from approximately 900° to 1000° C. for germanium and 0.2° C. from approximately 1400° to 1600° C. for silicon.

The usual type of temperature control for an electric furnace is of the "on-off" cycling type in which the heating elements are turned on at a certain minimum temperature and then turned off at a certain maximum temperature.

[Price 3s. 6d.]

Because of the lack of control of the temperature between the minimum and maximum limits, even though these limits are relatively close together, the on-off type of control is entirely unsatisfactory for the process above described. The present invention controls temperatures through continuous incremental variations in the electrical power input to the furnace. This continuous power variation control has been accomplished by adapting to precise automatic electronic control the well-known manual method of setting the output power of radio-frequency generators. In this manual method of setting generator power output, either the phase or the amplitude of the grid voltages to the "Thyratron" rectifier tubes of the d.c. voltage supply for the generator is adjusted to the setting at which the duty-cycle of each "Thyratron" is of such length that the average d-c power supplied to the generator by all the "Thyratron" tubes will be just sufficient to produce the desired radio-frequency power output. A "Thyratron" is a grid controlled, gas-filled, thermionic emission device. In the temperature control system of the present invention, the phase of the "Thyratron" grid voltages, after the initial manual setting, is electronically varied in response to an electrical signal generated by a temperature measuring device within the furnace. Thus, the input power to the furnace is precisely and automatically adjusted to compensate for any variations in the furnace temperature from the desired operating temperature.

It is one object, then, of the present invention to provide a precise and accurate temperature control system for radio-frequency induction furnaces and other types of electric furnaces.

It is another object of the present invention to provide an induction furnace which is suitable for manufacturing the monocrystalline ingots of semiconductor material used in the fabrication of bars and wafer segments for transistors and diodes.

It is still another object of the present invention to provide a means for controlling the temperature of the charge of an electric furnace to within 0.2° C. at temperatures from approximately 900° C. to approximately 1600° C.

It is still another object of the present invention to provide a means for controlling, to a high degree of accuracy, variations in the firing time and duty-cycle of gas-filled, grid controlled, thermionic emission devices in such a manner that their average power output is precisely controlled.

It is a still further object of the present invention to provide a means for accurately controlling the changes in temperature of a charge in an induction or other type of electric furnace according to a predetermined program of temperature changes.

The above objects together with other

objects and details of the present invention will become apparent from the following description when taken in conjunction with the accompanying drawings in which:

Figure 1 is a plot of amplitude against time for the various voltages and currents of a typical negative grid "Thyratron" tube of the type used in the temperature control system of the present invention;

Figure 2 is a schematic-diagrammatic illustration of one embodiment of the temperature control system of the present invention;

Figure 3 is a schematic diagram of the electrical circuit of a second embodiment of the temperature control system of the present invention including two additional temperature measuring methods;

Figure 4 is a vector diagram illustrating the various voltages of the phase shifting network portion of the circuit illustrated in Figure 3; and

Figure 5 is a schematic representation of a temperature changing mechanism which may be used with the temperature control system of the present invention.

With reference now to Figure 1, the input power control method of the present invention will be explained. The control function is achieved through an electrical signal which controls the conducting period of the one or more "Thyratron" rectifier tubes providing primary d.c. power to the furnace heating means. The "Thyratron" is a type of tube well-known in the electronic art. It has three elements, namely a grid, plate, and cathode, and is filled with an inert gas. One of its characteristics is that with a voltage applied between its plate and cathode elements, the tube will not conduct current until the grid voltage is made sufficiently positive for the tube to "fire," which voltage is known as the critical grid voltage. Referring to Figure 1, there is illustrated a plot of a typical critical grid characteristic 6 for a type of negative grid "Thyratron" suitable for use in the present invention. It can be seen that this critical grid voltage is dependent to some extent on the plate voltage (curve 1) applied to the tube in that, as the plate voltage increases, the critical grid voltage becomes more negative.

Another "Thyratron" characteristic is that, after the tube fires, the grid no longer controls the amount of current flowing through the tube and the tube continues to conduct even after the grid voltage has fallen below the critical grid voltage. Once the tube begins to conduct, the amount of current flow through the tube depends only on the magnitude of the plate voltage and the tube continues to conduct until the plate voltage drops to a value equal to the inherent voltage drop across the tube, approximately five to ten volts. Thus, it can be seen that the average d-c power output of a "Thyratron" rectifier can be controlled by controlling through grid voltage variations the time at

which the tube fires during each positive half-cycle of the a-c plate voltage. Figure 1 illustrates that these grid voltage changes may be either in phase or in amplitude to effect a change in firing time. Shown in the drawing are the curves of the a-c voltage 1, a negative d-c grid bias voltage 7 to hold the grid below the firing point, the a-c grid voltage signals 2, 3 and 4, and the plate current curve 5 for a negative grid "Thyratron." The grid voltage curves 2 and 3 illustrate the effect of a change in grid voltage amplitude. Both of these grid voltages are in phase with the plate voltage 1 but the voltage of curve 3 is greater in amplitude than the voltage of curve 2. With the voltage of curve 3 on its grid, the "Thyratron" will fire at the time indicated by the point at which this curve 3 crosses the critical grid voltage curve 6. This point is designated as 8. When the tube fires, the plate current flow rises immediately to the value indicated by the current curve 5 and continues to follow curve 5 until the tube is extinguished by the removal of the positive plate voltage. If a grid voltage of smaller amplitude, curve 2, is impressed on the grid, the tube will not fire until a later time designated by the cross-over point 9. It can easily be seen that different total amounts of plate current will flow during the plate voltage cycle according to the amplitude of the grid voltage of the "Thyratron."

The grid voltage curve 4 illustrates how the same plate current control can be exercised by shifting the phase of the grid voltage. The voltage of curve 4 is of the same amplitude as the voltage of curve 3, but it causes the "Thyratron" to fire earlier in the plate voltage cycle and to conduct more current during the cycle because the voltage of curve 4 is leading the voltage of curve 3 in phase and so reaches the critical grid voltage 6 at an earlier time designated as point 10. Thus, by controlling either the phase or the amplitude of the grid voltage, the total amount of plate current flow during each plate voltage cycle and therefore the average d-c power output of the tube over a number of plate voltage cycles can be controlled. It is to be understood that a sharp spike of voltage such as 11 will fire the tube just as well as the sine wave voltages of the other grid voltage curves 2, 3, and 4.

Turning now to Figure 2, a schematic-diagrammatic representation of one embodiment of the temperature control circuit of the present invention is shown in which the furnace controlled is of the induction type for purposes of illustrating the circuit. A radio-frequency generator 12 whose input power is controlled by "Thyratron" tubes 51, 52, and 53 as described above is used to heat the crucible 13 and charge (not shown) by means of the output coils 14.

The temperature of the crucible and the charge is measured by means of a thermo-

couple 15 which is placed in a cavity 16 of the crucible 13. In series connection with this hot junction thermocouple is a cold junction thermocouple 17 immersed in an ice-water bath 18. Because the temperature of melting ice is constant, this cold junction thermocouple 17 provides the necessary constant temperature reference for the system. As is well-known, a thermocouple arrangement such as this produces an emf proportional to and varying directly with the temperature of the hot junction. A thermocouple wherein one element is platinum and the other element is an alloy comprised of 90% platinum and 10% rhodium, provides a sensitivity in the order of ten microvolts emf change per degree centigrade change in temperature over the range of about 900° C. to 1400° C. and has been found quite satisfactory for use in the present invention.

As a means to detect temperature changes in the order of 0.2° C., i.e., a thermocouple voltage change of two microvolts, an extremely sensitive bucking voltage system is used consisting of the battery 19 and the voltage divider resistors 20 to 26 inclusive. By varying the resistance of an element, say 25, of the voltage divider network, the bucking voltage provided by the network, i.e., the voltage drop across the resistors 24, 25, and 26, can be controlled and made to cancel exactly the thermocouple emf at the desired temperature. Thereafter, any change in the thermocouple voltage output due to a temperature change in the crucible will be indicated as a d-c error voltage at the terminals 27 and 28 and its polarity will depend on whether the temperature change is an increase or a decrease. Since it is much easier to detect changes of from one to twenty microvolts from a zero potential level than to detect a change of this same order of magnitude from a 10,000 microvolt level, the bucking voltage network allows accurate detection of extremely small temperature changes.

This d-c microvolt indication of temperature change is then fed through lines 29 and 30 to a chopper circuit 31 of the non-rectifying vibrator type well-known in the art, (see *Radiotron Designer's Handbook*, Lanford-Smith, Fourth Edition, 1953, at page 1203), which has its vibration frequency controlled by the external excitation of its coil from an a-c voltage. The chopper 31 is synchronized at the power line frequency by the a-c voltage from the phase A power line 32 fed to the chopper excitation coil 33 through line 34. The phase of the chopper output depends on the polarity of the d-c signal fed into it and, therefore, the chopper output voltage will be an a-c voltage either in phase with the voltage of the chopper excitation coil 33 (phase A voltage) or 180° out of phase with the chopper excitation coil voltage as determined by the polarity of the input signal. This a-c voltage is then fed from

the chopper to an amplifier shaper circuit 35 where it is amplified and formed into a sine wave of the same phase as the chopper output voltage and of an amplitude which is proportional to the amplitude of the d-c signal appearing at terminals 27 and 28. This sine wave signal is next fed to the grid of one-half of the dual triode mixer tube 36. The other grid of tube 36 has impressed on it a sine wave signal derived from the phase A power line 32 but shifted in phase by a phase shifting network 37 so that the signals of the two grids are exactly 90° out of phase. The two cathodes of tube 36 are each connected to ground through their respective cathode resistors 38 and 39. The two plates of the tube 36 are tied together and connected to B+ through the load resistor 40. The output voltage from the plates through condenser 41 and line 42 is, then, a voltage which is proportional to the vector sum of the two input grid signals. This output is also a sine wave signal but its phase depends on the amplitude and phase of the grid signal from the chopper amplifier circuits 31 and 35. In this manner, there has been produced a sine wave signal whose phase changes with any crucible temperature change.

The variable phase sine wave voltage appearing on line 42 is next fed to the initial power control phase shift network 43 where its phase can be set as desired. (The proper setting of the phase of the output voltage from the phase shift network 43 will be discussed later).

Two sine wave voltage outputs are taken from the initial power control phase shift network 43. One of these output voltages, on line 118, is fed to the pulse forming network 44 whose output is a sharp "spike" pulse of voltage.

The second output, on line 45, is fed to the constant phase shift network 46 which also produces two output voltages. Both of these output voltages lag the input voltage to the network 46 in phase by exactly 120°. One of these outputs is fed through line 119 to

another pulse forming network 47 which produces a spike pulse of voltage at its output. This pulse lags the output pulse of the network 44 by exactly 120° of the mains cycle because of the phase shift introduced by the network 46. The second output of network 46 on line 48 is used as the input signal for still another 120° constant phase shift network 49.

The single output signal from the network 49 on line 120 when impressed on the input terminals of the pulse forming network 50 produces at the output terminals of the network 50 a third spike pulse of voltage which lags the pulse from network 44 by exactly 240° and lags the pulse from the network 47 by 120°.

In this way there have been produced three sharp pulses of voltage whose phase relationship corresponds to the phase relationship of the voltages of the three power lines 121, 122, and 123 supplying plate voltage to

the three "Thyratron" tubes 51, 52, and 53.

These sharp pulses of voltage are impressed on the grids of the "Thyratrons," 51, 52 and 53 through the lines 134, 135, and 136 respectively to control the firing times of the tubes.

The grids of all three "Thyratrons" 51, 52, and 53 are biased below the critical grid voltage by their connection through the resistors 54, 55, and 56 to a negative grid bias supply 57. Thus, the firing time of each "Thyratron" and, consequently, the average d-c power to the radio-frequency generator depends on the time of arrival, i.e. the phase with respect to the a-c power line voltage, of the spiked grid pulses which fire the tubes by causing their grids to become more positive than the critical grid voltage. Since the phasing of these grid pulses is a function of the thermocouple 15 voltage, there has been established a control system capable of regulating the furnace temperature through continuous control of the input power to the furnace. The control is to such a fine degree that changes can be produced from one cycle of input power to the next.

Although three "Thyratron" tubes connected as half-wave rectifiers are illustrated, the present invention is not to be construed as limited only to the use of such a rectifier circuit, for, by incorporating a lesser or greater number of pulse forming networks together with associated phase shift networks to produce the proper phase shifts for the several grid control voltages, the present temperature control system may be adapted to be used with either full-wave or half-wave rectifier circuits supplied from either single-phase or poly-phase power voltages.

The proper setting of the initial power phase shift network 43 mentioned above will now be discussed. The phase shift provided by the network 43 has been made manually variable in order that the temperature control system may be operated at its most sensitive point. The point of greatest system sensitivity occurs when the initial power phase shift network 43 is adjusted so that no error signal occurs at the terminals 27 and 28 when the temperature of the crucible 13 is at or near the mid-point of the temperature range to be used in growing the crystal. These mid-point temperatures are approximately 960° C. for germanium and approximately 1420° for silicon.

To accomplish the setting referred to above, the control of the bucking voltage network is set to indicate the desired operating temperature on the control dial and the switch 124 is opened to interrupt the error signal feedback loop and prevent any automatic adjustment of the initial power phase shift network 43 due to the error signal. With power now applied to the radio-frequency generator 12, the initial power phase shift network 43 is manually adjusted until the error signal of the feed-back loop is zero as indicated by the meter 125. At this point, the temperature of the crucible 13

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is the temperature indicated by the control dial of the bucking voltage network. The switch 124 is again closed and thereafter any change of crucible temperature will automatically be compensated for by the error signal to the initial power phase shift network 43. This adjustment places the system at its most sensitive operating point, as noted above, and, in addition, eliminates the danger of loss of control of the temperature over the range desired should the error signal from the chopper circuit 31 become so great that it overdrives the shaper amplifier 35.

A second embodiment of the temperature control of the present invention wherein a different means is used to control the phasing of the "Thyratron" firing pulses from the thermocouple voltage is illustrated in Figure 3. When the circuitry schematically diagrammed in Figure 3 is substituted for the chopper, amplifying and phasing portions of the circuit of Figure 2 between the terminals 27, 28, 58, and 59, the second embodiment is produced.

In this second embodiment, the variable amplitude and polarity d-c voltage appearing at the terminals 27 and 28 of Figure 2 is fed to a self-balancing potentiometer-recorder designated as 60 in Figure 3. Self-balancing potentiometer-recorders are devices well-known in the electrical art. (See M. B. Stout, *Basic Electrical Measurements*, New York: Prentice Hall, Inc., 1950, pages 174-178). Briefly, a self-balancing potentiometer-recorder is a type of instrument servo-mechanism wherein the input signal unbalances a resistance bridge network thereby creating an error signal which will then drive a small motor coupled to the moving contact of a potentiometer forming one element of the bridge circuit. When the error signal is produced, the sliding contact is moved along the potentiometer by the motor until the bridge is again in balance. The position of the potentiometer slider then indicates the magnitude and polarity of the input signal.

For use in the present invention, the motor of the self-balancing potentiometer-recorder 60 has coupled to it the slider contact 61 of an additional potentiometer 62. The potentiometer 62 is an element of a variable d-c grid bias supply comprised of the battery 63 and the variable resistors 64 and 65. By this arrangement, the sliding contact 61 provides a grid bias potential which is proportional to the output voltage of the thermocouple 15. The condenser 68 serves the purpose of providing greater sensitivity to sudden changes. The tube 66 is connected as an ordinary d-c amplifier with a resistor 69 from the grid to ground and a resistor 70 from the cathode to ground. The plate is connected to B+ voltage through the d-c coil 71 of the saturable reactor 72. The saturable reactor 72, together with the transformer 77 secondary coils 73 and 74, and the resistor 75 forms a continuously variable

phase shifting circuit. Through this circuit, the phase of an applied a-c voltage can be controlled by the amplitude of the d-c voltage in the coil 71 of the saturable reactor 72. An a-c voltage from the terminal 59 is impressed on the primary coil 76 of the transformer 77. The secondary coils 73 and 74 of the transformer 77 produce a voltage similar to the voltage at terminal 59 across the series network comprised of secondary coil 78 of the saturable reactor 72 and the resistor 75. The phase of the output voltage between the terminal 58 and ground depends on the reactance of the coil 78 which is controlled by the d-c current of the coil 71. (See R. R. Benedict, *Introduction to Industrial Electronics*, New York: Prentice Hall, 1951, pages 353 and 354 for an explanation of the change in reactance of the a-c coil of a saturable reactor by a change in current in the d-c coil). The phase shifting action of this network can best be explained by reference to the vector diagram of Figure 4.

In Figure 4, the voltages induced in the coils 73 and 74 of the transformer 77 are represented by the vectors 73^1 and 74^1 respectively. The sum of the voltage drops across a-c coil 78 of the reactor 72 and the resistor 75 must be equal to the voltage drop across the transformer coils 73 and 74, and the voltage across the resistor 75 will always be 90° out of phase with the voltage across the reactor coil 78. These two voltages are then represented by the vector 75^1 for the drop across the resistor 75, and 78^1 for the voltage drop across the reactor coil 78. The voltage at the output terminal 58 will be the voltage between ground and the junction point of coil 78 and the resistor 75 and is therefore represented by the vector 58^1 from the junction point of the vector 73^1 and 74^1 (ground) and the junction of vectors 75^1 and 78^1 . Now, if the reactance of coil 78 is reduced, the voltage drop across this coil will become smaller as represented by the vector 78^{11} . Since the sum of the vector voltages across the coil 78 and the resistor 75 must be equal to the sum of the vector voltages across the coils 73 and 74, and since the voltage across the resistor 75 must be at 90° with the voltage across the coil 78, the vector 75^{11} represents the voltage across the resistor 75. The vector 58^{11} now represents the output voltage which has been changed in phase. Thus, it can be seen that the magnitude of the d-c current determines the phase of the output voltage at terminal 58.

Because of the time lag introduced into the system by the self-balancing potentiometer-recorder when using the embodiment of Figure 3, an additional radio-frequency feed-back loop is provided to reduce any tendency of the system to oscillate. This additional feed-back circuit is shown in Figure 3. The circuit measures the actual radio frequency output of the generator 12 and by its action limits the radio-frequency power change to approximately

the amount needed to effect the desired temperature change thus eliminating over-correction and oscillation in the system.

5 The radio-frequency output level is detected by a single turn pickup coil 79 placed near the generator output coils 14. The radio-frequency energy induced in the pickup loop 79 is rectified by the diode tube 80, filtered in the network composed of the radio-frequency choke 81, resistor 82, and capacitors 83, 84 and 85 and fed to the voltage divider network consisting of resistors 86 and 87 connected between B+ voltage and ground. Any change in the d-c voltage produced from the rectified and filtered radio-frequency signal changes the current flow through the resistor 87 and thus the potential at the slider arm 88 of the potentiometer 87 which is used to set the feed-back level. The voltage from the slider arm 88 is fed through the resistor 89 to produce another control bias at the terminal 90 which may be impressed on the grid of tube 66 in Figure 3 to control the "Thyratron" grid voltage phasing.

25 Still a third feed-back system may be incorporated into the temperature control system of the present invention. This third feed-back circuit, which measures the temperature of the crucible by the color of the crucible, is illustrated as part of Figure 3. A quartz rod 91 is placed in another cavity 92 of the crucible 13 to direct infra-red radiation from the hot crucible to a photocell 93 which is sensitive to such radiation. The circuit comprised of the battery 94, the phototube 93, and the resistor 95 forms a voltage divider circuit wherein the voltage drop across the phototube is governed by the amount of infra-red radiation incident upon the tube which is in turn governed by the temperature of the crucible. Any change in the voltage drop across the phototube 93 due to a change in the crucible temperature causes a change in the voltage across the resistor 95 and thus a change in the output signal through the capacitor 96 to the amplifier 97. The output signal of the amplifier is differentiated by the capacitor 98—resistor 99 network and then fed into the control system of Figure 3 at terminal 90. This feed-back system, because of the differentiation of its output signal, provides correction proportional to the rate of change of crucible temperature. This feed-back signal also tends to compensate for the time lag introduced into the thermocouple feed-back loop by the potentiometer-recorder 60.

55 As stated before, it is often desirable to vary the temperature of the furnace according to a predetermined program of temperature changes. The programming device schematically illustrated in Figure 5 provides the means for producing controlled temperature changes. This programmer produces changes in the crucible temperature in the following manner.

65 The two precision potentiometers 100 and 101 have impressed across their terminals an a-c voltage from the power lines 102 and 103

through the transformer 104. Because these two potentiometers are connected in parallel across the secondary coil 105 of the transformer 104, their voltages are of exactly the same phase. Therefore, if the sliders 106 and 107 of the potentiometers 100 and 101 contact their respective potentiometers at the same relative point, no voltage will be supplied to the input terminals 108 and 109 of the amplifier 110 since the sliders to which these terminals are connected will be at the same potential. However, if one of these sliders 106 is displaced, a voltage is developed between the terminals 108 and 109. The phase of this voltage will be determined by the direction of displacement of slider 106 and its amplitude will be determined by the amount of displacement. For example, if slider 106 is displaced toward the top of the drawing, the signal across the terminals 108 and 109 will be in phase with the signal across the secondary coil 105 of the transformer 104. However, if slider 106 is displaced toward the bottom of the drawing, the phase of the voltage to the terminals 108 and 109 will be reversed and it will be 180° out of phase with the voltage of the coil 105.

Any signal voltage at the terminals 108 and 109 is amplified by the amplifier 110 and fed to the grids of two triode tubes 112 and 113. The tubes 112 and 113 have their cathodes connected together and to ground through the common cathode resistor 126. The grids likewise are connected together and to ground through a common grid resistor 127. The plates of the two tubes are connected to opposite ends of another secondary coil 114 of the same transformer 104 which supplies voltage to the two precision potentiometers 100 and 101. The center tap 115 of the secondary coil 114 is connected to ground through the rotor coil 111 of a balancing motor designated generally as 128, so that the plate voltages of the two tubes 112 and 113 are 180° out of phase. Because the grid signal voltage is derived from the same transformer 104 as the plate voltage, the grid voltage on the tubes 112 and 113 will always be in phase with the plate of one of the tubes and 180° with the other, and only the tube in which the grid voltage and plate voltage are in phase will conduct current. The direction of displacement of the slider 106 determines the phase of the grid voltage to the tubes 112 and 113 and, therefore, the direction of displacement of the slider 106 determines which of the tubes, 112 or 113, conducts.

By referring to the diagram of Figure 5, it can easily be seen that any current which flows in the rotor coil 111 of the balance motor 128 must also flow through either the upper or lower half of the transformer secondary coil 114. Thus, the current of the rotor coil 111 must be of one of two phases each 180° different from the other and the phase of this current depends on whether it is the upper or

lower half of coil 114 through which current flows or which tube, 112 or 113, is conducting. In other words, the phase of the current in the rotor coil 111 of the balance motor 128 is determined by the direction of displacement of the slider 106. As shown in Figure 5, slider 106 is displaced by means of the cam 131 and follower mechanism 132, but any of several means may be used for this purpose.

The voltage of the stator coil 116 of the balance motor 128 is produced from the power supply lines 102 and 103 and, were it not for the condenser 117 inserted in the line to the stator coil 116, the voltage would be either in phase or 180° out of phase with the rotor coil 111 voltage. However, the condenser 117 shifts the stator coil 116 voltage in phase by 90°. Since any currents which flow in the rotor and stator coils 111 and 116 of the balance motor 128 will always be 90° out of phase with each other, the rotor of the balance motor 128 will turn when current flows in the rotor coil 111 and its direction of rotation will be determined by whether the current in the rotor coil 111 is lagging or leading the current in the stator coil 116.

Coupled to the rotor shaft 129 of the balance motor 128 are the slider 130 of the resistor 21 in the bucking voltage network of Figure 2 and the slider 107 of the "follow-up" potentiometer 101. The coupling of sliders 130 and 107 to the shaft 129 may be either direct or by means such as gearing depending on the construction of the potentiometers 21 and 101. When current flows in the rotor coil 111 as the result of a displacement of the slider 106, the rotor shaft 129 turns and there is produced a change in the error signal appearing at the terminals 29 and 30 in Figure 2 due to a movement of the slider 130 which produces a change in the bucking voltage of the bucking voltage network of Figure 2. The rotor shaft 129 will continue to turn and the temperature error signal in the system will continue to change until the slider 107 coupled to the rotor shaft 129 is displaced from its original contact point on the potentiometer 101 to a contact point at which its potential is exactly the same as the potential of the slider 106. At this point, no further signal is developed between the terminals 108 and 109, and thus no grid voltage signal is fed to the tubes 112 and 113. Without a grid voltage, no current will pass through either of the tubes, and, consequently, no current will flow in the rotor coil 111. Of course, when current no longer flows in the rotor coil 111, the rotor 129 no longer turns and the temperature error signal of the temperature control system ceases to change.

In the embodiment of the temperature control system of the present invention illustrated in Figure 3 wherein a self-balancing recording potentiometer 60 is used in the error signal feed-back loop, automatic control of the temperature

may be incorporated by coupling the rotor shaft 129 of the balance motor 128 to the slider 133 of the potentiometer 64 instead of to the slider 130 of the potentiometer 21 as illustrated in Figure 5.

By means such as the cam 131 and follower 132 mechanisms coupled to slider 106 wherein variations in radius along the circumference of cam 132 are proportional to the temperature changes to be produced, the signals for a predetermined program of temperature changes can be introduced into the system. Through use of a similar cam and follower to produce signals for pull-rate changes in the pull-rate control system of the crystal pulling machine and use of a small motor to drive both cams at the same speed, the crystal pulling procedure becomes an almost completely automatic process.

It is to be understood that the phase shifting, pulse forming, amplifier and shaper circuits referred to in the above description and illustrated in the various figures of the drawings merely in block form need not be of any specific type, but may be any of the of the many types well-known in the art.

Thus, there have been disclosed several specific embodiments of the present invention for holding the temperature of an electric furnace to within $\pm 0.2^\circ$ C. of any desired temperature and a specific method of varying this controlled temperature according to a predetermined program of changes. These specific embodiments of the present invention have been described using a radio-frequency induction furnace, specific phasing and feed-back circuitry and a specific method for introducing a program of temperature changes; however, many changes, alterations and substitutions still within the scope of the present invention will be apparent to those skilled in the art. Therefore, it is not intended that the present invention be limited to the specific embodiment illustrated herein but that it be limited only as set forth in the appended claims.

WHAT WE CLAIM IS:—

1. A system for controlling the temperature of an electric furnace in which the electrical power to said furnace is supplied through at least one grid controlled, gaseous discharge type device, comprised of means producing a DC voltage indicative of furnace temperature, means for producing a DC error voltage which varies in magnitude and polarity as a function of the difference between actual furnace temperature and a predetermined reference temperature, means for changing said DC error voltage to an AC voltage of phase and magnitude controlled by said DC error voltage, means including a thermionic emission device for deriving the vector sum of said AC voltage with an extrinsically supplied alternating voltage to produce a sine wave signal with a phase which reflects changes in furnace temperature, and means including phase shifter means for

lower half of coil 114 through which current flows or which tube, 112 or 113, is conducting. In other words, the phase of the current in the rotor coil 111 of the balance motor 128 is determined by the direction of displacement of the slider 106. As shown in Figure 5, slider 106 is displaced by means of the cam 131 and follower mechanism 132, but any of several means may be used for this purpose.

The voltage of the stator coil 116 of the balance motor 128 is produced from the power supply lines 102 and 103 and, were it not for the condenser 117 inserted in the line to the stator coil 116, the voltage would be either in phase or 180° out of phase with the rotor coil 111 voltage. However, the condenser 117 shifts the stator coil 116 voltage in phase by 90°. Since any currents which flow in the rotor and stator coils 111 and 116 of the balance motor 128 will always be 90° out of phase with each other, the rotor of the balance motor 128 will turn when current flows in the rotor coil 111 and its direction of rotation will be determined by whether the current in the rotor coil 111 is lagging or leading the current in the stator coil 116.

Coupled to the rotor shaft 129 of the balance motor 128 are the slider 130 of the resistor 21 in the bucking voltage network of Figure 2 and the slider 107 of the "follow-up" potentiometer 101. The coupling of sliders 130 and 107 to the shaft 129 may be either direct or by means such as gearing depending on the construction of the potentiometers 21 and 101. When current flows in the rotor coil 111 as the result of a displacement of the slider 106, the rotor shaft 129 turns and there is produced a change in the error signal appearing at the terminals 29 and 30 in Figure 2 due to a movement of the slider 130 which produces a change in the bucking voltage of the bucking voltage network of Figure 2. The rotor shaft 129 will continue to turn and the temperature error signal in the system will continue to change until the slider 107 coupled to the rotor shaft 129 is displaced from its original contact point on the potentiometer 101 to a contact point at which its potential is exactly the same as the potential of the slider 106. At this point, no further signal is developed between the terminals 108 and 109, and thus no grid voltage signal is fed to the tubes 112 and 113. Without a grid voltage, no current will pass through either of the tubes, and, consequently, no current will flow in the rotor coil 111. Of course, when current no longer flows in the rotor coil 111, the rotor 129 no longer turns and the temperature error signal of the temperature control system ceases to change.

In the embodiment of the temperature control system of the present invention illustrated in Figure 3 wherein a self-balancing recording potentiometer 60 is used in the error signal feed-back loop, automatic control of the temperature

may be incorporated by coupling the rotor shaft 129 of the balance motor 128 to the slider 133 of the potentiometer 64 instead of to the slider 130 of the potentiometer 21 as illustrated in Figure 5.

By means such as the cam 131 and follower 132 mechanisms coupled to slider 106 wherein variations in radius along the circumference of cam 132 are proportional to the temperature changes to be produced, the signals for a predetermined program of temperature changes can be introduced into the system. Through use of a similar cam and follower to produce signals for pull-rate changes in the pull-rate control system of the crystal pulling machine and use of a small motor to drive both cams at the same speed, the crystal pulling procedure becomes an almost completely automatic process.

It is to be understood that the phase shifting, pulse forming, amplifier and shaper circuits referred to in the above description and illustrated in the various figures of the drawings merely in block form need not be of any specific type, but may be any of the of the many types well-known in the art.

Thus, there have been disclosed several specific embodiments of the present invention for holding the temperature of an electric furnace to within $\pm 0.2^\circ$ C. of any desired temperature and a specific method of varying this controlled temperature according to a predetermined program of changes. These specific embodiments of the present invention have been described using a radio-frequency induction furnace, specific phasing and feed-back circuitry and a specific method for introducing a program of temperature changes; however, many changes, alterations and substitutions still within the scope of the present invention will be apparent to those skilled in the art. Therefore, it is not intended that the present invention be limited to the specific embodiment illustrated herein but that it be limited only as set forth in the appended claims.

WHAT WE CLAIM IS:—

1. A system for controlling the temperature of an electric furnace in which the electrical power to said furnace is supplied through at least one grid controlled, gaseous discharge type device, comprised of means producing a DC voltage indicative of furnace temperature, means for producing a DC error voltage which varies in magnitude and polarity as a function of the difference between actual furnace temperature and a predetermined reference temperature, means for changing said DC error voltage to an AC voltage of phase and magnitude controlled by said DC error voltage, means including a thermionic emission device for deriving the vector sum of said AC voltage with an extrinsically supplied alternating voltage to produce a sine wave signal with a phase which reflects changes in furnace temperature, and means including phase shifter means for



producing from the sine wave signal time spaced voltage spikes for application to the grid of the gaseous discharge type device.

2. A system as claimed in claim 1, wherein the electrical power to said furnace is controlled during each cycle of the power voltage frequency.

3. A system as claimed in claim 2, having means continuously changing said d-c voltage to a first a-c voltage, a second a-c voltage, said modulating means combining said first and second a-c voltages whereby the phase of the combined voltages depends on the amplitude and phase of said first a-c voltage, means forming said combined voltages into pulses, which, on being applied to the grid of said at least one thermionic emission device, control the conductive period of said at least one device during each cycle of said a-c power voltage thereby controlling the electrical power to said furnace.

4. A system wherein said means forming said combined voltages into pulses also effects phase shifting said combined voltages.

5. A system as claimed in Claim 1, in which there are a plurality of grid controlled, gas-filled thermionic emission devices, means continuously changing said d-c voltage to a first a-c voltage, a second a-c voltage, the modulating means combining said first and second a-c voltages whereby the phase of the combined voltages depends on the amplitude and phase of said first a-c voltage, the a-c power voltage applied to each of said plurality of thermionic emission devices, and a plurality of means for phase shifting and forming said combined voltages into a plurality of time spaced pulses which, on being applied to the grids of said plurality of thermionic emission devices, control the conductive period of each of said devices during each cycle of said a-c power voltage thereby controlling the electrical power to said furnace.

6. A system as claimed in Claim 5, including a radio-frequency generator.

7. A system as claimed in Claim 1, including self-balancing potentiometer means producing a second d-c voltage proportional to said d-c error voltage, means amplifying said second d-c voltage, means whereby the phase of said a-c control voltage is controlled by the amplitude of said amplified second d-c voltage, an a-c power voltage applied to said at least one thermionic emission device, and means for phase shifting and forming said phase controlled a-c voltage into pulses which on being applied to the grid of the thermionic emission device, control the conductive period of said device during each cycle of said a-c power voltage thereby controlling the electrical power to said furnace.

8. A system as claimed in Claim 1, in which the electrical power to said furnace is supplied through a plurality of grid controlled, gas-filled thermionic emission devices, including a

self-balancing potentiometer means producing a second d-c voltage proportional to said d-c error voltage, means amplifying said second d-c voltage, an a-c control voltage, means whereby the phase of said a-c control voltage is controlled by the amplitude of said amplified second d-c voltage, the a-c power voltage applied to each of said plurality of thermionic emission devices, and a plurality of means for phase shifting and forming said phase controlled a-c control voltage into a plurality of time spaced pulses which, on being applied to the grids of said plurality of thermionic devices, control the conductive period of each of said devices during each cycle of said a-c power voltage thereby controlling the electrical power to said furnace.

9. A system as claimed in Claim 7, including infra-red sensing means associated with said furnace, radiation sensitive means producing a voltage varying with the amount of said radiation, means amplifying said varying voltage, differentiating means producing a pulse proportional to the rate of change of said radiation, the means amplifying said second d-c voltage also amplifying said pulse.

10. A system as claimed in Claim 1, including a radio-frequency generator and generator output coils associated therewith, comprised of means producing a d-c voltage indicative of furnace temperature, means cancelling said d-c voltage at a preset temperature and producing a d-c error voltage with variations in temperature from said preset temperature, self-balancing potentiometer means producing a second d-c voltage proportional to said d-c error voltage, radio-frequency power detection means in close proximity with said generator output coils, means rectifying the voltage induced in said detection means, means producing a third d-c voltage proportional to said rectified voltage, means amplifying said second and third d-c voltages, means whereby the phase of said a-c control voltage is controlled by the amplitude of said amplified second and third d-c voltages, an a-c power voltage applied to said at least one thermionic emission device, and means for phase shifting and forming said phase controlled a-c control voltage into pulses, which on being applied to the grid of said at least one thermionic emission device, control the conductive period of said at least one device during each cycle of said a-c power voltage thereby controlling the electrical power to said furnace.

11. A system as claimed in Claim 10, including infra-red radiation sensing means associated with said furnace, radiation sensitive means producing a voltage varying with the amount of said radiation, means amplifying said varying voltage, differentiating means producing a pulse proportional to the rate of change of said radiation, means amplifying said second d-c voltage, said third d-c volt-



age, and said rate of change pulse, means whereby the phase of said a-c control voltage is controlled by the amplitude of said amplified second d-c voltage, and said third d-c voltage, and said rate of change pulse.

12. A system as claimed in any of Claims 1 to 11, which includes a servo-mechanism and means for programming temperature changes in said furnace, said system thereafter accurately controlling the temperature of said furnace at the changed temperature.

13. A system for controlling the temperature of an electric furnace in which the electrical power to said furnace is supplied through at least one grid controlled, gas-filled thermionic emission device, comprised of means cyclically supplying power to said furnace through said at least one thermionic emission device, means producing a voltage which is a function of the difference between actual furnace temperature and a reference temperature, and means applying said voltages to said at least one thermionic emission device to control the conductive period thereof during each cycle whereby the electrical power to said furnace is continuously controlled.

14. A system for controlling the temperature of an electric furnace in which the electrical power to said furnace is supplied through at least one grid controlled, gas-filled thermionic emission device, comprised of means producing a d-c voltage indicative of furnace temperature, means producing therefrom a d-c error voltage with variations in the furnace temperature from a preset temperature means including a chopper for deriving an a-c control voltage to be applied to said at least one thermionic emission device, and means for modulating said a-c control voltage by said d-c error voltage thereby continuously controlling the electrical power to said furnace.

15. A system for controlling the temperature of electric furnaces substantially as herein described and as illustrated in the accompanying drawings.

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